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WATER REQUIREMENTS OF THE JORDANIAN NUCLEAR POWER PLANT

Eng. T. Tawalbeh[1*] and **Prof. W. Abu-El-Sha'r**[2]

[1] Department of Civil Engineering, Jordan University of Science and Technology, Irbid, Jordan.

[1] Current Position: Water Studies Researcher, Jordanian Uranium Mining Company, Amman, Jordan.

[2] Professor, Department of Civil Engineering, Jordan University of Science and Technology, Irbid, Jordan.

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ABSTRACT

Nonconventional water resources have been allocated by the government of Jordan to provide cooling water for the first Jordanian Nuclear Power Plant (NPP). These resources included reclaimed wastewater from AsSamra Wastewater Treatment Plant, and groundwater from the deep aquifers (more than a 1000 meter depth) in the vicinity of the NPP site. This decision generated great attention and its soundness has been questioned by many skeptics of the nuclear program in Jordan. To address these concerns, this study focused on the reliability of the quality and quantity of the allocated resources. Statistical analyses using six different distribution functions (Normal, Log-Normal, 3 Parameter Gamma, Log-Pearson Type Three, Gumbel, and General Extreme Value) were performed for the nine regulated quality parameters of AsSamra WWTP effluent and compared with the relevant Russian cooling water standards since Russian reactors are chosen. Results indicated that some parameters (Total Dissolved Solids, Chloride, total and carbonate hardness) concentrations did not meet the Russian standards and thus require a tertiary treatment. In addition, a 3D finite difference flow model (Processing MODFLOW) was developed to study the deep aquifers response and to investigate the resulted drawdown under different pumpage scenarios representing the allocated quantities. The resulted drawdowns exceeded the one tenth of the aquifer thickness limit that is commonly used and the maximum allowable pumpage rates were smaller than the allocated ones.

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*** Corresponding Author:** Eng. T. Tawalbeh, t.m.tawalbeh@gmail.com

INTRODUCTION

The government of Jordan represented by Jordan Atomic Energy Commission (JAEC) decided to build the first nuclear power plant (NPP) that consists of two reactors, of which the first unit to be operable by 2024 the other one by 2025. The NPP will be located less than 10 km to the south of Qasr Amra, 70 km from Amman, and 60 km from AsSamra wastewater treatment plant (WWTP) (JAEC, 2014). In addition, JAEC identified the Russian company (Rosatom) that manufactures and provides (AES-92 model VVER-1000) with 1000 Mega Watt electric (MWe) capacity for each reactor as a technology provider (Araj, 2014) (Araj, 2008).

Providing Jordan's NPP with cooling water is a challenge due to the extreme scarcity of water resources in the country; Jordan is considered as one of the most poorest countries in water (Al-Kharabsheh & Ta'any, 2009). Therefore, JAEC decided to use nonconventional water resources, such as reclaimed wastewater and groundwater from deep aquifers as cooling waters. The government of Jordan has allocated 30 million cubic meter per year (MCM/yr) from AsSamra WWTP effluent and 15 MCM/yr from groundwater (GW) from deep aquifers near the NPP site (Araj, 2014) (Toukan, 2015). Using treated Wastewater (WW) and GW for NPP cooling are solutions that were also suggested by International Atomic Energy Agency (IAEA) to avoid fresh water usage (IAEA, 2012).

Treated WW has been used for thermoelectric power plants; about fifty thermoelectric power plants in the USA use treated WW for cooling purposes (Ethan & Zhang, 2008). But Palo Verde NPP at Arizona State is the only NPP that cools nuclear reactors with treated municipal WW; it is the largest NPP in the USA and produces about 4030 MWe (Dalrymple, 2013).

Treated municipal WW contains high concentrations of suspended and dissolved solids, and nutrients which increase the challenge of its usage in recirculating cooling system since it must at least meet secondary WW treatment standards and it may require a tertiary treatment to prevent corrosion, fouling, and scaling in pipes and heat exchange equipments (Theregowda, Vidic, Dzombak, & Landis, 2014). Therefore, the treated WW must meet certain specified standards before using it for cooling. Herein, AsSamra effluent will be studied and statistically compared with the Russian cooling water standards which include limits for nine different quality parameters, namely: TDS, pH, SO_4^{2-}, PO_4^{3-}, Cl^-, Dissolved Oxygen, total and carbonate hardness, and NO_3^-.

The reliability of using the reclaimed wastewater from AsSamra WWTP effluent depends on the availability of the allocated quantities for the life time of the reactor. Thus, the communities generating the wastewater have been explored.

The allocated quantities for cooling water from deep groundwater aquifers need special attention since there is a general lack of studies on these aquifers and very few deep wells are available in the study area. The aquifer system underlying the NPP site vicinity and Jordan in general consists of a three aquifer system, namely: the upper, middle, and lower (sandstone) aquifers (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010). Among these aquifers, the sandstone formations (deep aquifers with more than a 1000 m depth) are poorly studied and very little is used for supplying water. Nevertheless, enormous GW quantities at the deep aquifers are expected but are untapped yet because the water tables of sandstone aquifers are very deep (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010)

and little is known about its quality. To date, no computer model for the deep aquifer exists, simply due to the lack of data and information on these aquifers. To bridge the gap in information, a three dimensional groundwater model (Processing MODFLOW) was developed to study the deep aquifers response and to investigate the resulted drawdown under different stresses using the scarce data available as provided by the Ministry of Water and Irrigation (MWI).

The objective of this research is to study the reliability of the uncommonly allocated cooling water resources (quantitiy and quality).

RELATED WORK

2.1 Using Reclaimed Wastewater for Cooling Thermoelectric Power Plants

Only one nuclear power plant uses reclaimed wastewater for cooling (Palo Verde) at Arizona (Ethan & Zhang, 2008). Following are some findings about using wastewater for cooling NPP's focused on Palo Verde NPP:

(Hamilton & Bingham, 1979), publisehd a study about Palo Verde NPP reactors and operation system. First they mentioned that wastewater was used before in cooling power plants but not in such a climate and quantitiy (124.35 MCM/yr) as in Palo Verde NPP. The plant consists of three nuclear pressurized water reactors (PWR), each produces about 1300 MWe, operating since 1982. The plant operates as follows: first water is pumped through the reactor core to be heated by nuclear fuel to (317 ˚C) under about (2250 psia) pressure to prevent boiling while pumped through steam generator where supplied water heated to produce steam that piped to trubines for electicity production then steam is condensed back to water to repeat the process, the water used for steam condensation (cooling water) is piped to mechanical draft cooling towers to be cooled by evaporation then returnes to plant to repeat the cycle.

According to (IAEA, 2012) IAEA published a technical report studying water management of NPP during all phases: construction (flushing phase), operation (condenser cooling) and maintenance. Water required for Operation: the quantity of water required for cooling the condenser is a function of: NPP capacity, NPP efficiency, the need of water treatment before using it, NPP location and site conditions. The report suggested the following solutions for NPP water usage: raising NPP efficiency, find alternatives cooling systems for once through cooling, find alternative cooling water sources and cogeneration. To avoid fresh water usage for cooling the report suggested other sources of water: mine and groundwater, wastewater, seawater, internally generated wastewater and blow down water. They also concluded that recirculating system (wet cooling towers) requires much less water than once through system thus it has been increasingly used and considered as an alternative for once through system. Finally, the report mentioned that using sewage for cooling NPP like in Palo Verde NPP has some challenges like: the need of chemical treatment, corrosion control, etc.

(Dalrymple, 2013) published a magazine article about Palo Verde NPP experience in cooling nuclear reactors with treated wastewater and the possibility of applying that in Jordan. It concluded that Palo Verde receives its cooling water from Arizona's largest wastewater treatment plant which treats water by three stages (trickling filter, softening and gravity filtration), the effluent characteristics in 2012 are as follows: Alkalinity (as $CaCO_3$), Calcium (as $CaCO_3$), Magnesium (as $CaCO_3$), Silica, Phosphate, total dissolved

solids (TDS) are: (42, 87, 33, 4, 0.3, 1001) mg/L respectively. The water is pumped to onsite reservoirs at Palo Verde plant, to be used then for cooling until it becomes supper concentrated; it's sent to evaporation ponds. The article also concluded that wastewater qualities in Jordan and Palo Verde are comparable and similar, but it's more concentrated in Jordan. It supplement that such a model can be done in Jordan but it's important to understand and determine the needs of cooling water quality, storage capacity, and staffing. It admitted that sewage is rarely used for cooling nuclear power plants due to the difficulties and the expense; additional cost related to treatment, staffing and chemicals.

(NEI, 2013) fact sheet mentioned that the only nuclear power plant uses reclaimed municipal wastewater for cooling is Palo Verde NPP at Arizona desert, two proposed nuclear reactors scheme to use municipal wastewater for cooling at Florida State. It also mentioned that the nuclear power plants use moderate amounts of cooling water and minimal land area in comparison with other electricity generation plants; it is a valuable option for the water constrained countries due to the high electricity production and moderate water consumption.

2.2 Groudwater

The MWI has allocated 15 MCM/yr from groundwater deep aquifers (sandstone formations) for NPP cooling purposes (Araj, 2014). Following are two studies about: using groundwater for cooling (which is uncommon to be used for NPP's cooling) and groundwater deep aquifers in Jordan (which are rarely studied):

(Arad & Olshina, 1984) considered that the location of any future nuclear power plant in israel will be in the Negev desert where there is no surface water to provide the plant with cooling water, the only two alternatives of cooling water are: piped in Mediterranean seawater and brackish groundwater -with about 4000 mg/L salinity-. They examined the Judea group aquifer –which was considered as a single aquifer- to provide sufficient amounts of cooling water along the nuclear plant lifetime without causing extreme drawdown in the regional water table. They considered the effects of using cooling system (totally wet cooling system consuming 50 MCM/yr). Finally they concluded that using brackish groundwater is a desirable alternative for cooling a nuclear plant.

(Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010) studied the sandstone aquifer system and produced 3D modeling of aquifers and geometry formations of Jordan and the surrounding area, and simulated groundwater flow. In this research deep sandstone formations were studied focusing on the little known (Khreim, Kurnub, and Ram) groups -which bear fossil water- to look for new groundwater resources and study the geological and hydrological characteristics of the aquifers. The study identified very specific places for groundwater abstraction (drilling wells) according to quantity, quality, cost, and sustainability standards. Two models were constructed because the study area is widely extended to the neighboring countries (recharge area): the first model is Marthe model "the extended one" operated by BRGM staff it depends only on natural boundaries and extended to Saudi Arabia with 592 km x 810 km window size and 2 km x 2 km grid size, and the second one is MODFLOW model "limited one" operated by MWI staff studying the northern part of the extended model (without Saudi Arabia area) with 484 km x 478 km window size and the same grid of Marthe model. It is worth mentioning that some faults were assumed to be impervious limits for groundwater flow

other considered as leaky or has partial transmissivity. In MODFLOW model they calibrated the model for transient flow and steady state flow, noting that determining the steady state end is hard.

2.3 Reliability of Treated Wastewater

(Messaoud, Bachir, & Maurice, 2013) used normal, lognormal and gamma distribution laws to test BOD_5, COD, and TSS concentrations for Khenchela the activated sludge WWTP in Algeria. The goodness of fit was tested using (Kolmogorov-Smirnov, Cramer-Von Mises, Anderson Darling, and Watson) tests; Kolmogorov test gave much higher power for normal and lognormal distributions than Chi-squared test. They found that lognormal distribution is the most representative of the effluent parameters which has already been studied by many scientists and concluded that lognormal gives a good overall fit to concentration values; it's the most used for water quality modeling. Their results for BOD_5 and COD effluents were in compliance with Algerian Standards but not for the TDS due to grit chamber problems.

MATERIALS AND METHODS

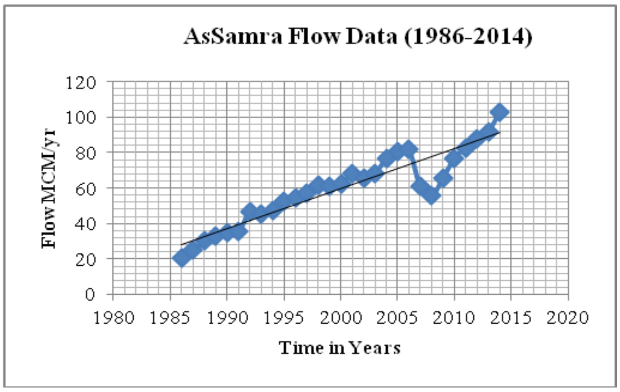
3.1 AsSamra Analysis

The analysis performed in this study focused on exploring the reliability of using treated WW from AsSarmra WWTP as a supply source for cooling the reactors; and on the availability of the allocated quantities of GW (15 MCM/yr) from adjacent deep aquifers. For the first objective, statistical analyses have been performed on available data to identify the best statistical distribution that best fits the available data for each parameter and then to use this distribution for predicting the design parameter based on 95% confidence interval.

3.1.1 AsSamra's Effluent Quantity

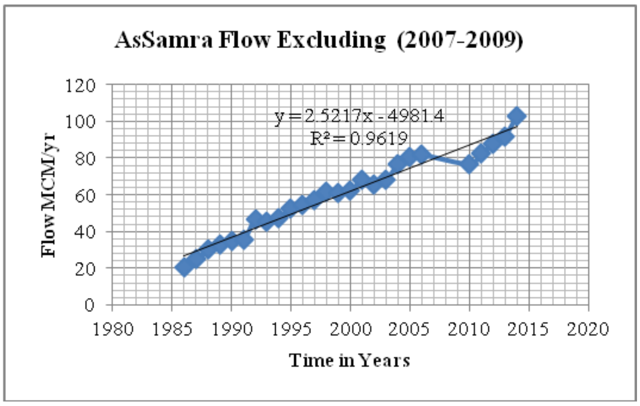
AsSamra plant was built at 1986 with stabilization ponds system which was replaced at 2004 with the activated sludge modern plant to enhance quality and quantity of AsSamra effluent. The construction has two expansion phases; phase I (2004-2008) with 100 Million Cubic Meters (MCM) annual treatment capacity and phase II (2012-2015) with 133 MCM annual treatment capacity; the plant expansion meets the increasing inflow requirements (MIGA, 2013). AsSamra flow data collected during (1986-2014) are shown in Figure 1.

Figure – 1: *AsSamra Annual Inlet Flow Versus Time*



The flow increases annually except at the period (2006-2008) due to phase I construction processes. At 2008 AsSamra modern plant started operating, since then the flow returns to increase. The flow has an inflection point at the year 2007 which resulted into two flow behaviors (1986-2006) and (2007-2014); the flow starts to accelerate at 2007 (it has a higher slope). But for being conservative, the statistical analysis used the largest period of recorded data, the flow data since 1986 till 2014 was studied excluding the years (2007-2009) as presented in Figure 2.

Figure – 2: *AsSamra Flow Data Excluding the Years (2007, 2008 and 2009)*



AsSamra flow is increasing linearly. The linear relationship determined from Figure 2 was used to predict the flow data for future. According to the linear relationship it is expected that AsSamra plant will treat about 125 MCM/yr by 2025 and more than 130 MCM at 2030.

3.1.2 AsSamra Quality Reliability Analyses

Studying the reliability of treated WW is a critical issue when the treated WW is reused. In treatment plants the reliability is defined as "the percent of time that effluent concentration meets specified permit requirements" (Messaoud, Bachir, & Maurice, 2013); herein the reliability is important to test how AsSamra treated effluent meets the required Russian vender cooling water standards. Reliability (R) is defined as the probability of success and equals:

$R = 1 - P(F)$ ………………………………………………………………………………… (1)

Where P(F): probability of failure (risk); failure occurs when treated water effluent parameters (Ce) exceeds the relevant standards (Cs): F = (Ce>Cs) (Messaoud, Bachir, & Maurice, 2013):

The most commonly used "Weibull" formula was used in studying AsSamra parameters. Weibull formula (Bedient & Huber, 1988):

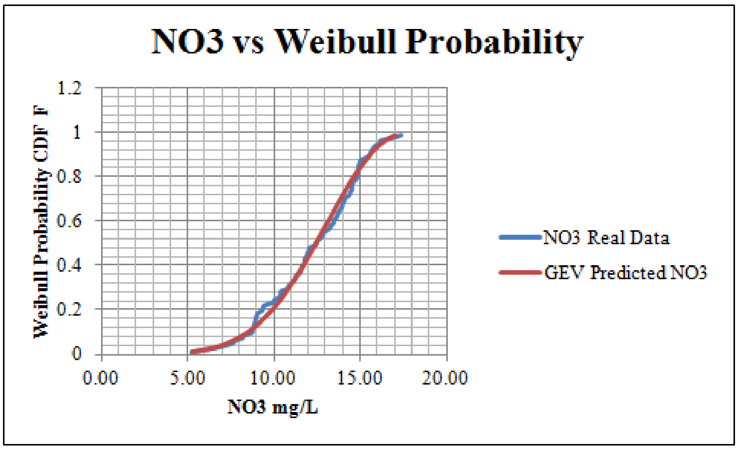
$F = 1 - 1/T = 1 - (m/n+1)$ ……………………………………………………………… (2)

Where F: Weibull probability (CDF: cumulative density function); T: return period; m: rank from 1 to n; n: number of records.

First, data were ranked from largest to smallest (largest datum has m = 1 and smallest has m = n). Return period and Weibull probability were calculated according to equation (2) given above. Then, the real data for AsSamra WWTP effluent is plotted versus the Weibull probability as calculated using equation (2). For example, In Figure 3 the curve in blue shows the data of AsSamra effluent nitrate parameter which were drawn versus the

Weibull probability as calculated in equation 2, this is called the real data. The curve in red shows the predicted data after applying them in a specified distribution using the smadaonline.com website -a website that contains a collection of tools including statistical calculation tools that draw and predict data for specified distributions.-

Figure – 3: *AsSamra NO_3 Real and GEV Predicted Data Versus Weibull Probability*



Reliability is extremely sensitive to the selected probability distribution function (Messaoud, Bachir, & Maurice, 2013). Six statistical distributions (Normal, Log-Normal, 3 Parameter Gamma, Log-Pearson Type Three (LP3), Gumbel, and General Extreme Value (GEV)) were used in studying AsSamra effluent reliability analysis using the EasyFit 5.1 Professional software. These distributions are the most used and applicable for water modeling (Bedient & Huber, 1988) (Millington, Samiran, & Simonvic, 2011). The distributions were tested using the Kolmogorov-Smirnov (KS) test. The KS test examines the data and determines the maximum vertical distance between the real data graph and the predicted data graph. The distribution that best fits the real data is the one that gives the least maximum distance between real and predicted curves.

Nine parameters including: total dissolved solids (TDS), pH, sulfates (SO_4^{2-}), nitrates (NO_3^-), phosphates (PO_4^{3-}), chloride (Cl^-), dissolved oxygen (DO), and total and carbonate hardness are considered. Data on AsSamra effluent parameters were collected from Ministry of Water and Irrigation for the duration from 2008 till 2015 (since the modern plant started operating) and the missing data of (dissolved oxygen, chloride, total and carbonate hardness) were requested from Royal Scientific Society (RSS) which only records (min, max, and average) for three individual years these data are helpful and can give an indication about chloride and hardness reliability.

The statistical analysis for the nine parameters we done and shown in following subsections:

3.1.2.1 Nitrate (NO_3^-)

The Russian cooling water standards set 15 mg/L as the highest NO_3^- acceptable concentration. Figure 4 shows AsSamra NO_3^- effluent readings for the duration from Jan-2008 till Aug-2014 along with the required Russian standards of 15 mg/L (green horizontal line). Ten out of Eighty NO_3^- readings exceeded the standard, thus the risk = 12.5%, and the reliability = 87.5%. Most of readings are less than the allowable concentration especially after the year 2011. The best distribution that gives the highest rank of goodness of fit for

these data is GEV according to KS test. The PDF and CDF for NO3- values were plotted using EasyFit software as shown Figure 5 and Figure 6 respectively. From the CDF plot at 50% reliability, the TDS reading is 12 mg/L; which means 50% of the readings are less than or equal 12 mg/L (for assessment). At 95% reliability, the TDS reading is 16 mg/L that considered as (design parameter). Real and GEV predicted data were shown previously in Figure 3.

Figure – 4: *NO_3 Concentrations of AsSamra Effluent (Jan-2008 to Aug-2014)*

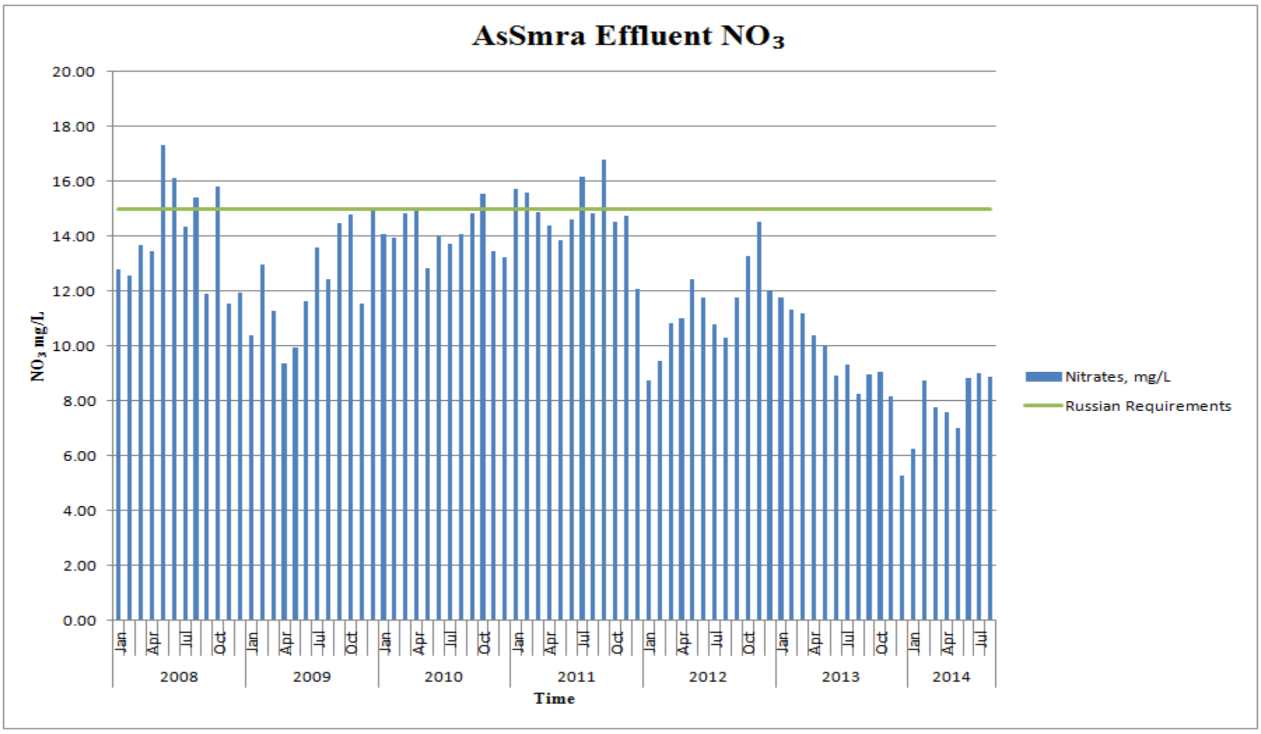


Figure – 5: *The PDF of AsSamra Effluent NO_3 (GEV Distribution)*

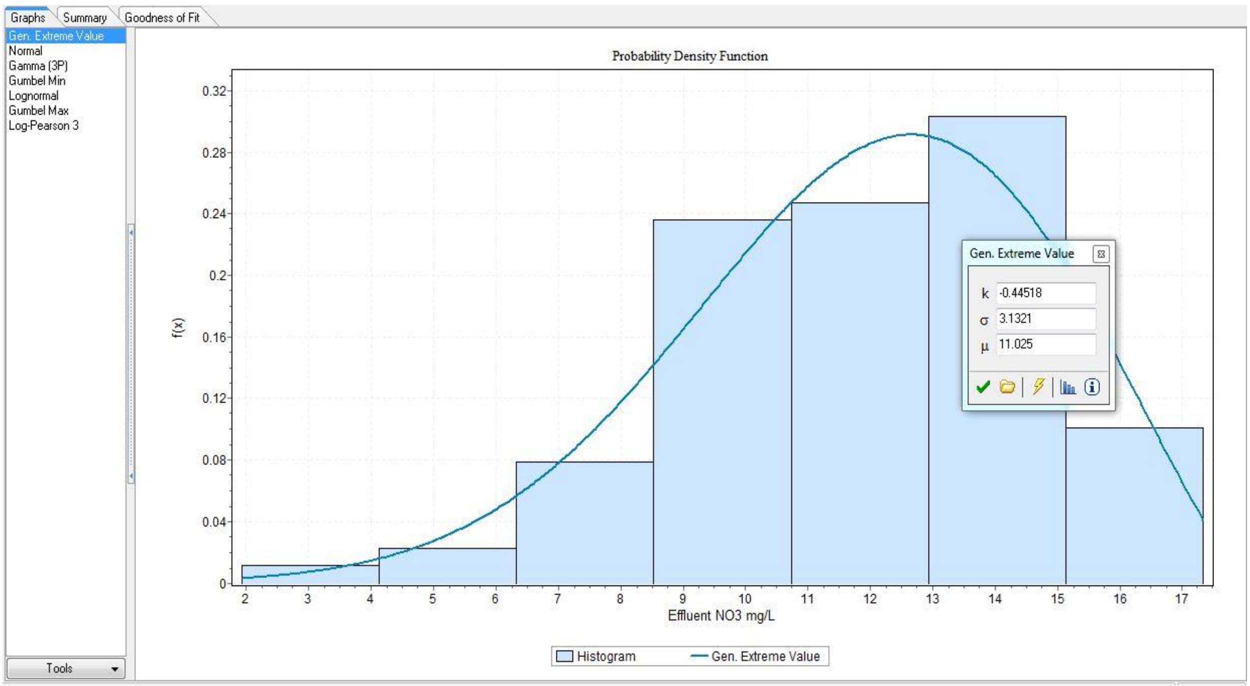
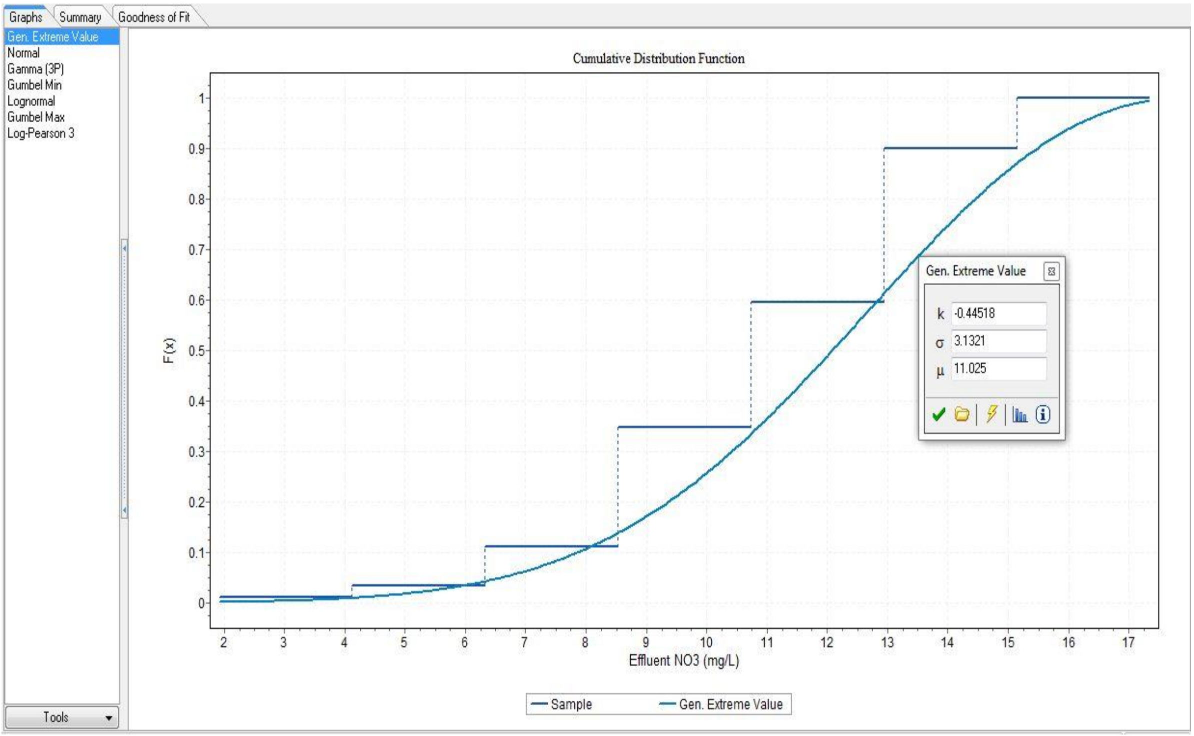


Figure – 6: *The CDF of AsSamra Effluent NO_3 (GEV Distribution)*



3.1.2.2 Total Dissolved Solids (TDS)

AsSamra effluent TDS concentrations were available for the period (2009 - 2015), the required Russian standards of 800 mg/L. From 2009 till 2013 the effluent TDS exceeded this standard and then it started to decrease to reach values less than 800 mg/L at 2015. Seventy one out from seventy seven of TDS readings exceeded this standard. Thus, the Risk = 71/77 = 92.3%, and therefore Reliability = 7.7%. The most representative statistical distribution is (GEV) that describes TDS concentrations. The CDF was plot using EasyFit software at 50% reliability, the TDS reading is 1140 mg/L; 50% of the readings are less than or equal 1140 mg/L (for assessment). At 95% reliability, the TDS reading is 1250 mg/L which considered as (design parameter).

3.1.2.3 pH

According to the Russian standards for cooling water, the pH values must be limited between 6.5 and 8.5. AsSamra effluent pH reading during Apr-2007 and Aug-2014 were all within the range; pH has 100% reliability. The GEV distribution has the highest rank according to the KS test. At 50% and 90% reliability pH readings are 7.1 and 7.24 respectively.

3.1.2.4 Phosphate (PO_4^{3-})

Data of PO_4 concentration of AsSamra effluent from Jan-2010 till April-2015 are collected and studied. Twenty one out of sixty readings exceeded the relevant Russian standards for cooling water (4 mg/L); thus the risk = 35%, and reliability = 65%. The PO4 concentration started to reduce after 2012. Log-Pearson Type 3 (LP3) and GEV have the highest ranked distribution functions that describe AsSamra PO4 readings. At 50% reliability PO4 reading is 3.2 mg/L, at 95% reliability PO4 reading is 6.4 mg/L.

3.1.2.5 Sulphates (SO_4^{2-})

The data analysis of AsSamra SO_4^{2-} influent concentration from Aug-2011 till May-2015 are collected and studied. For the given time period, the sulfates concentrations are far less than the maximum allowable concentration of 500 mg/L since 160 mg/L is the maximum recorded SO_4^{2-} readings. Risk = 0%, reliability = 100%. According to KS test, Gamma 3P has the best goodness of fit in describing SO_4^{2-} concentration and GEV comes in rank two, but the reliability readings of the two distributions are almost the same, therefore GEV will be considered. At 50% and 95% reliabilities SO_4 readings are 77 mg/L and 120 mg/L respectively.

3.1.2.6 Dissolved Oxygen (DO)

During (March-2009 – Feb-2010) and (May-2013 – May-2014) periods DO was tested 10 times and 20 times respectively by the Royal Scientific Society (RSS). The maximum recorded readings for these two periods are 5.4 mg/L and 9.5 mg/L respectively. The maximum DO readings are far less than the allowable maximum DO concentration (20 mg O_2/L) which means that the DO is 100% reliable.

3.1.2.7 Chloride (Cl^-)

During (March-2009 – Feb-2010) and (May-2013 – May-2014) chloride was tested 6 times and 13 times respectively by RSS. The minimum recorded readings for these two testing periods are 171 mg/L and 257 mg/L respectively. Which are higher than the allowable maximum chloride concentration (150 mg/L) which means that the chloride reliability is 0%.

3.1.2.8 Hardness

AsSamra effluents of Ca^{2+}, Mg^{2+}, HCO_3^-, and SO_4^{2-} parameters were tested by RSS for three individual years. The Russian relevant standards set 7 meq/L and 2.5 meq/L as the maximum allowable total and carbonate hardness, respectively. AsSamra effluent carbonate hardness exceeded the Russian standards.

3.2 Reliability of Groundwater from Deep Aquifers

The reliability of the allocated water from the deep aquifers (mainly sandstone) in the vicinity of the NPP site has been investigated by developing a three dimensional groundwater flow model for evaluating the availability and sustainability of the allocated groundwater under the proposed pumpage rates. Previous groundwater modeling in the area used either MODFLOW or PARFLOW codes (Al-Kharabsheh, 1999) (Abu-El-Sha'r & Hatamleh, 2007) (Abu-El-Sha'r & Rihani, 2007), MODFLOW has been used herein since it's widely used and user friendly. Currently, no models for the deep aquifers of interest exist and there is a general lack of data available on these deep aquifers. This highlighted the need for building a model to be used for the assessment.

3.2.1 The Deep Aquifers in Jordan

The aquifer system underlying Jordan consists of three systems: upper aquifer system, middle aquifer system, and lower sandstone aquifer system. The sandstone aquifers are the deepest (more than a 1000m deep) and oldest water formations at Jordan with age

ranges between 5000 and 20000 year. The sandstone complex underlay all Jordan and extends to the neighboring countries, it consists of two groups, namely Ram-Disi and Kurnub-Zarqa.

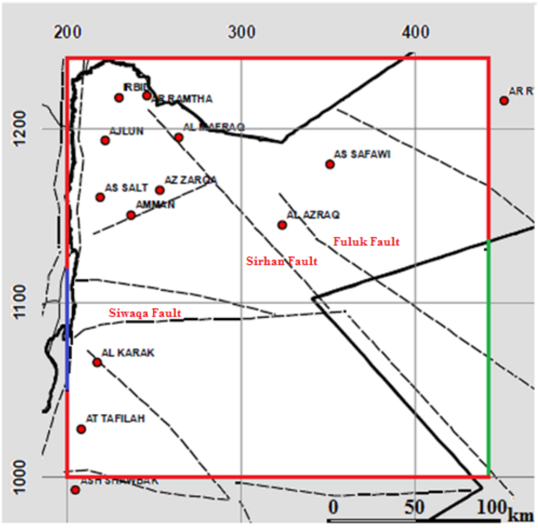
The limits of catchment areas and basins of upper and middle GW systems lost their importance at the lower formations which act as one GW basin reaching (Dead Sea basin) in the west. In these deep formations, groundwater flows from the East at neighboring countries where it is recharged to the West to reach Dead Sea and Azraq/Sirhan graben (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010).

The fossil nonrenewable sandstone formations are little studied and investigated. It contains enormous groundwater amounts but the high depths of water table makes withdrawal from the deep aquifers economically and technically difficult and therefore these aquifers are untapped yet.

3.2.1.1 Location

Ram group sandstone underlay all Jordan and widely extends to the neighboring countries. This made investigating the aquifer characteristics especially (the transparency and the aquifer boundaries) difficult and thus the vertical and horizontal extensions must be limited for model constructing (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010). The study area herein is highlighted in Figure 7.

Figure – 7: *Modeled Area with Boundary Conditions and the Main Faults Affect the Studied Area*



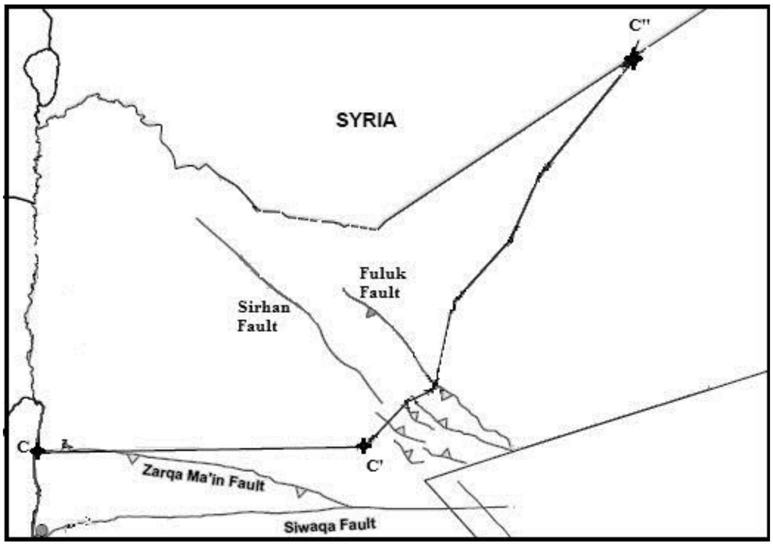
3.2.1.2 Geological Structure

The deep sandstone aquifer complex consists of packages of sandstone formations from Cambrian to Silurian (Ram-Disi and Khreim formations; Khreim is an aquitard) overlain by Lower Cretaceous formation (Kurnub-Zarqa). The sandstone aquifers are very deep at some areas mainly at the east and northern east of Jordan and shallower in other areas at south and central of Jordan with 1000 – 2500 m depth. The thickness of Ram aquifer also varies between 1000 m and could reach more than 2000 m. At about 100 km to the east of Amman, Azraq graben caused more than 2 km vertical uplift which made Ram aquifer exploitation at that area recommended and the most favorable. At the drastic uplift

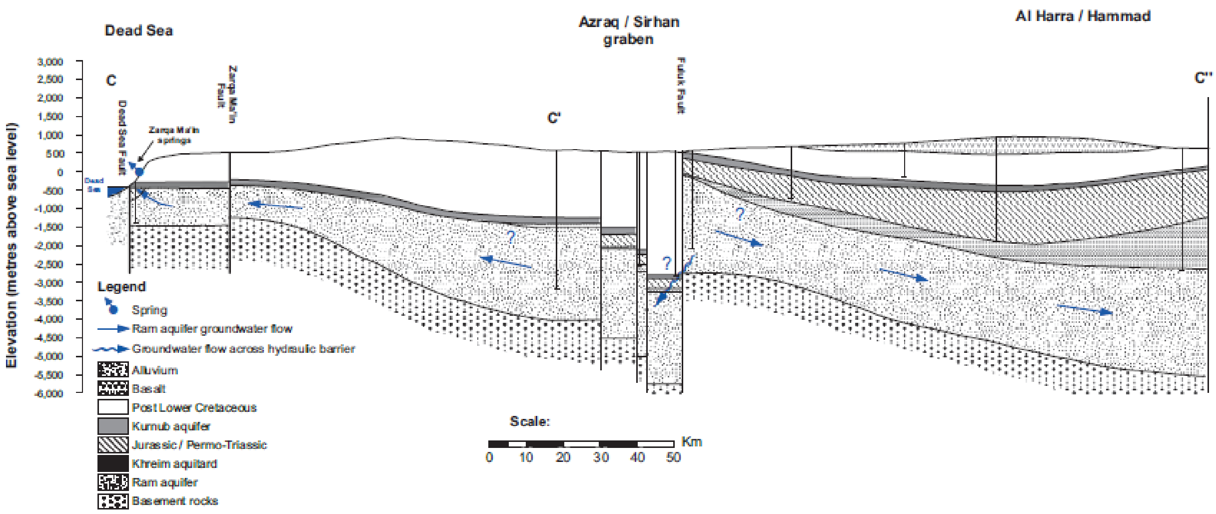
the depth to Ram aquifer is less than 1000 m and water table is less than 100 m below land surface (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010). Figure 8 shows the vertical uplift of Ram aquifer. A deep well (named AZ1) penetrating Ram aquifer about 100 km to the East of Amman confirmed the drastic uplift of Ram formation at that area. AZ1 well has 902 m total depth (<1000 m), and 62 m water level below ground level (<100 m) (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010) (Charalambous, 2016).

Figure – 8: *Groundwater cross sections show the vertical uplift at Azraq Sirhan graben.* ***a:*** *a simplified map,* ***b:*** *Dead Sea–Azraq–Hamad, geological–hydrogeological section (Charalambous, 2016)*

8 – a



8 – b



3.2.1.3 Faults

The major faults systems affecting groundwater flow in the area studied in this research are: Sirhan/Zarqa fault, Fuluk fault, and Siwaqa fault, these faults are shown in

Figure 7. The Fuluk fault extends from Azraq to Saudi Arabia with 100 km extending and 3000 m vertical uplift acts as a groundwater barrier because the hydraulic characteristics differ from north and south of the barrier (Al-Kharabsheh, 1999). The east-west Siwaqah fault with 60 km distance from Dead Sea to Jebel Siwaqa is not completely impervious and was fractured during tectonic events and made pathways for groundwater flow causing lateral offsets (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010).

3.2.1.4 Recharge, Discharge

Recharge refers to "the volume of infiltrated water that reaches the water table and becomes a portion of groundwater flow system" (Anderson & Woessner, 1991). In this study, the recharge of the deep aquifers from rainfall is very little and neglected. The deep aquifers are mainly recharged from the neighboring countries. Recharge can occur as a specified head specifically a constant head boundary which can act as an inexhaustible source or sink of GW- (Anderson & Woessner, 1991) (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010).

Discharge refers to "the water moving upward across water table to the unsaturated zone" (Anderson & Woessner, 1991). The major discharge of Ram group is the Dead Sea and mainly (Wadi Mujib). Groundwater abstraction at the neighboring countries is neglected because of the deep water level.

3.2.1.5 Hydraulic Parameters

At Ram formation the conductivity doesn't vary significantly with depth, the horizontal and vertical conductivities (Kh and Kv) are in general similar, thus the aquifer is assumed to be an isotropic. At southern Jordan, the Ram aquifer has conductivity values that range between 0.5 m/d and 8.5 m/d (most are below 3.5 m/d) with Kh mean value equals to 1.5 m/d. But the conductivity observed by AZ1 well penetrating the deep aquifers at Azraq area is 0.27 m/d as determined by the Ministry of Water and Irrigation. The storage coefficient is $7.2*10^{-4}$ m^{-1} and the specific yield is 7% (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010).

3.2.1.6 GW Quality

The sandstone aquifers' water quality was characterized as follows: Ram (very good), Khreim (poor), Zarqa (brackish, poor to fair) and Kurnub (fair to good). Khreim is an aquitard but the upper part is porous and saturated with (1200-10000 mg/L TDS -brackish to saline water-) while Ram aquifers water is considered to be fresh water with (170-1020 mg/L TDS) (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010). However, (Salameh, Alraggad, & Tarawneh, 2014) reported that the deep groundwater salinity ranges from brackish to saline, and specifically water from Ram aquifer changes from fresh at the southern part of Jordan to saline at northern part. AZ1 deep well penetrating Ram aquifer -about 100 km to the East of Amman- has 1560 mg/L TDS tested at 2002 by Ministry of Water and Irrigation (MWI). This gives an indication about the salinity of Ram aquifer water (brackish water) (Eraifej, 2006).

3.2.2 Groundwater Deep Aquifers Modeling

3.2.2.1 Conceptual Model

The conceptual model of deep aquifers for this study consists of one confined layer; Ram sandstone layer underlain by the basement complex. The recharge and discharge of this aquifer system are represented as constant heads.

The modeled area is relatively large with an area of 240 x 240 km^2 to include the major faults recharge and discharge areas.

3.2.2.2 Flow Governing Equation

The general form of governing equation is derived by water balance and Darcy's law and it describes the three dimensional GW flow through the porous media. Following is the steady state governing equation (Anderson & Woessner, 1991):

$$[\partial/\partial x * (kx * \partial h/\partial x)] + [\partial/\partial y * (ky * \partial h/\partial y)] + [\partial/\partial z * (kz * \partial h/\partial z)] + R = 0 \quad \ldots\ldots\ldots\ldots(3)$$

Where K: hydraulic conductivity, (L/T) unit. Kx, Ky and Kz: hydraulic conductivities along x, y and z coordinates axes. $\partial h/\partial x$: hydraulic gradient. *R:* Source/sink term (T^{-1}).

The hydraulic conductivity can be determined by steady state calibration and after steady state solution, the transient form is solved. In this case transient form could not be solved because the deep aquifers are not exploited yet, and no drawdown's were observed.

3.2.2.3 Model Input

The model covered an area of 240 km x 240 km which is divided to 120 columns and 120 rows, the total number of cells is 14400 cells. The layer thickness is 1000 m.

The boundary conditions are set as follows: constant head boundary conditions are in the East and West of the studied area; it presents the recharge area at the East where flow comes from, and discharge area at the West at Dead Sea where groundwater flows out. No flow boundary conditions are at the north, south, northwestern, and southwestern (where it meets a regional groundwater divide) of the domain.

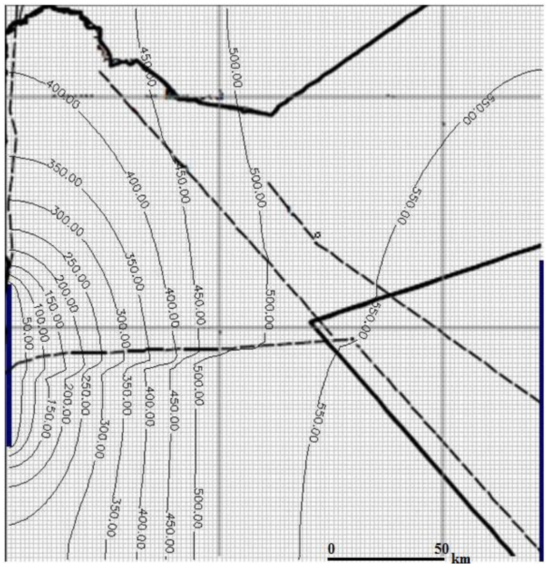
3.2.2.4 Steady State Calibration

In steady state calibration the input data parameters (hydraulic conductivity, specific storage, and recharge) were adjusted until the calculated heads simulated by MODFLOW match the available field measured heads (Al-Kharabsheh, 1999). But the deep aquifers are poorly studied and observed therefore the base map of head contour considered in this study is similar to the one calculated by Barthelemy and others (2010) (Barthelemy, Buscarlet, Gomez, Janjou, Klinka, Lasseur, Le Nindre, & Wuilleumier, 2010).

The hydraulic conductivities were calibrated by trial and error till GW contours have the general head contour behavior focusing on AZ1 cell (the only observed point at the study area). The head observed by AZ1 well is 523 m and the conductivity is 0.27 m/d as tested by MWI. The simulated head contour map is shown in Figure 9.

The hydraulic conductivity ranges between 0.05 m/d and 0.38 m/d, it is larger at the east of the modeled area and smaller at the southern west, it was simulated (0.05 - 0.1) m/d near the Dead Sea.

Figure – 9: *Simulated Head Contours Map of Ram Aquifer for the Modeled Area, the Selected Cell Presents AZ1 Well*



The faults were simulated as semi-permeable boundary by giving the cells along faults a very low hydraulic conductivity. The semi permeable faults are calibrated by setting one of each five cells –along the fault- as permeable. Three main faults were taken in consideration and simulated as semi-permeable barriers (Fuluk, Sirhan and Siwaqa), the fault effect is obvious at the head contours: the head contours tend to be parallel to Siwaqa fault as shown in Figure 10. Fuluk fault enlarges the drawdown; it affects the drawdown as there is a mirror well to AZ1 pumping well.

3.2.2.5 Transient Calibration

Most calibrations are performed for steady state and a second calibration for transient set (Anderson & Woessner, 1991). In steady state the hydraulic conductivity is calibrated until the simulated head map match the (reference map). Then the hydraulic map resulted from steady state calibration is used as a starting heads (initial heads) for transient simulation to calibrate (specific yield and storage coefficient) till the simulated drawdown meets the previously observed one (Al-Kharabsheh, 1999). Thus, the transient simulation requires a set of observed pumping rate data through long time to compare the simulated drawdown with the measured drawdown. This is not available in this study; the deep aquifers have not been exploited yet and no drawdown data were assigned.

3.2.2.5 Model Prediction

The aim of this step is to study and evaluate the model response and investigate the resulted drawdown under three different stresses representing three pumping scenarios. The first scenario represents using the groundwater from these aquifers as a redundant source of cooling water source of 30 MCM/yr, which is the total amount required annually for cooling the NPP. The second scenario is pumping the 15 MCM/yr which is the amount set by the Government of Jordan. The third scenario represent pumping 9.4 MCM/yr which is the maximum allowable pumpage that resulted in drawdown equals to 10% of aquifer thickness. The pumpage rates were withdrawal from AZ1 which was treated as a pumping well, the head and drawdown were observed at its cell.

100 m was considered as the maximum allowable drawdown assuming that the drawdown should not exceed 10% of aquifer thickness. Therefore the scenarios were applied and the resulted drawdowns were compared with this limit.

The first scenario caused 319.2 m drawdown which is considered as very high and serious drawdown, a 15 MCM/yr pumping rate resulted in 165 m drawdown which also exceeds the drawdown limits. Finally, 9.4 MCM/yr was identified as the maximum allowable pumpage rate with 100 m drawdown. The head contour maps resulted from the three stresses are shown in Figures 10, 11, and 12, respectively.

Figure – 10: *Simulated Head Contour Map with 30 MCM/yr Pumping Rate from AZ1*

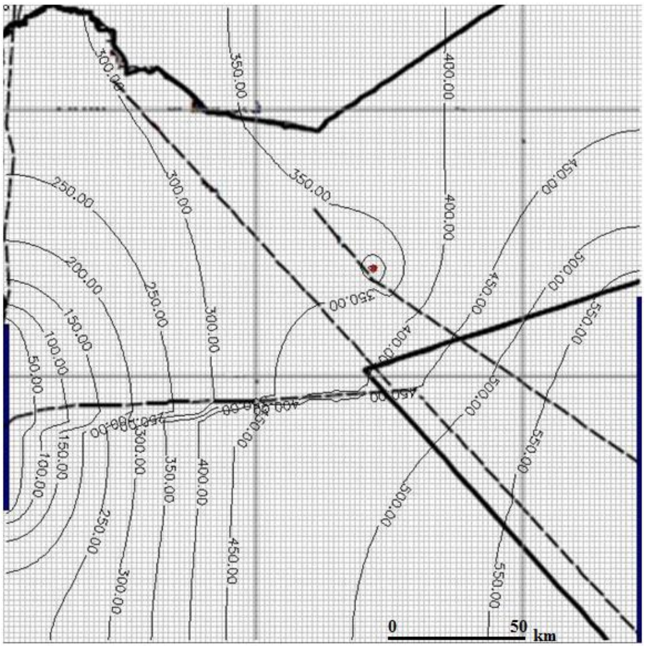


Figure – 11: *Simulated Head Contour Map of 15 MCM/yr Pumping Rate Withdrawal from AZ1 Well*

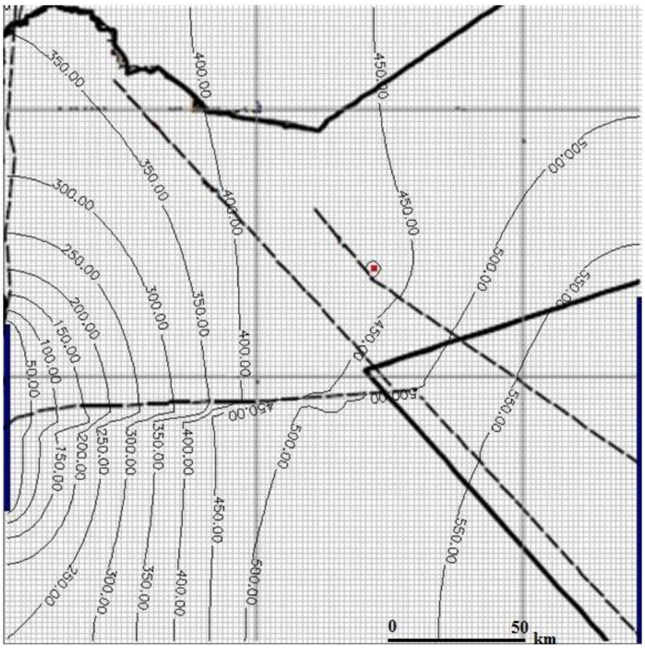
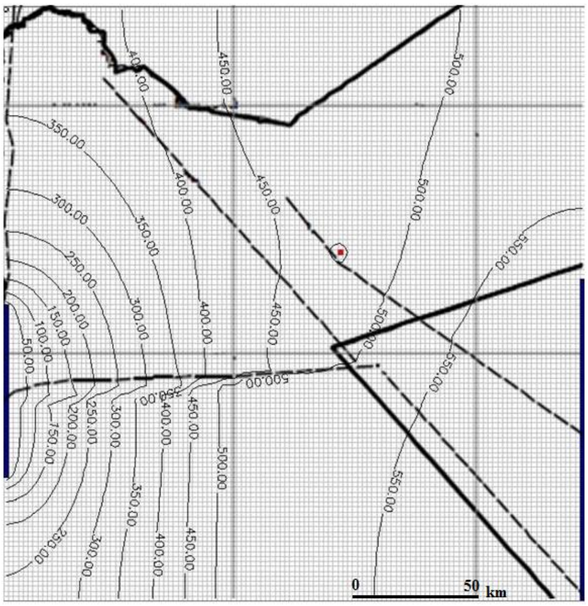


Figure – 12: *Simulated Head Contour Map of 9.4 MCM/yr Pumping Rate from AZ1 Well*



RESULTS AND DISCUSSION

4.1 AsSamra Reliability Analysis Results

Table 1 summarizes AsSamra studied parameters, and testing period for each parameter in addition to the required standards, reliability assessment, and design parameter. GEV distribution is the most representative of AsSamra effluent parameters since it gave the best goodness of fit according to the KS test.

The reliability analysis of AsSamra treated effluent shows that some parameters (hardness, carbonate hardness, TDS, and chloride) exceeded the allowable relevant Russian standards for cooling water. This means that AsSamra effluent needs further treatment before using it in cooling the nuclear reactors; it needs a tertiary treatment facility.

Table – 1: *AsSamra Effluent Parameters Summary Table*

Pmmeter	Russian Standard	Min – max readings	Testing period	Distribution	Reliability	Design Parameter 95%	Assessment 50%
TDS	800 mg/L	693 – 1280	Jan' 09 - May' 15	GEV	8%	1250 mg/L	1140 mg/L
pH	6.5-8.5	6.8 - 7.27	Aug' 07 - Aug' 14	GEV	100%	7.22	7.1
NO_3	15 mg/L	5.26 – 17.34	Jan' 08 - Aug' 15	GEV	85%	16 mg/L	12 mg/L
P-PO_4	4 mg/L	1.08 – 6.51	Jan' 10 - Apr' 15	LP 3, GEV	70%, 66%	6.2 mg/L	3.3 mg/L
SO4	500 mg/L	38.2 – 160	Aug' 11 - May' 15	Gamma 3P, GEV	100%, 100%	120 mg/L	77 mg/L
Cl	150 mg/L	171 – 382	Mar' 09 - Mar' 10	-*	0%	-	-
		257 – 357	May' 13 - May' 14				
DO	20 mg O_2/L	3.7 - 5.4	Mar' 09 - Feb' 10	-	100%**	-	-
		0.2 - 9.5	May' 13 - May' 14				

Total hardness	7 meq/L	4.152 - 7.38	Mar' 09 - Mar' 10	-	-	-	-
		5.69 - 7.44	Apr' 12 - Mar' 13				
		4.93 - 6.96	May' 13 - May' 14				
Carbonate hardness	2.5 meq/L	3.67-4.31	Mar' 09 - Mar' 10	-	0%	-	-

*****All Cl readings are greater than 150 mg/L (the maximum allowable concentration) so it is definitely 0% reliable otherwise the min, max, average concentrations and number of tests are only given therefore the PDF and CDF could not be drawn. ******Maximum recorded DO readings are much lower than the Russian standards therefore it is 100% reliable.

4.2 Groundwater Deep Aquifers Modeling Results

The first scenario (30 MCM/yr) caused 319.2 m drawdown which is considered as very high and serious drawdown, a 15 MCM/yr pumping rate resulted in 165 m drawdown which also exceeds the drawdown limits. Finally, 9.4 MCM/yr was identified as the maximum allowable pumpage rate with 100 m drawdown.

The three scenarios and the resulted drawdowns are shown in Table 2.

Table – 2: *Groundwater Modeling Summary Table*

Pumping Rate (MCM/yr)	Head (m)	Drawdown (m)	Drawdown Percentage to Aquifer Thickness
15	365	160	16%
30	205.8	319.2	32%
9.4	425	100	10%

CONCLUSION

This study focused on the reliability of using the treated municipal WW from AsSamra WWTP, and GW from deep fossil sandstone aquifers for cooling the Jordanian NPPs.

The quantity of AsSamra WWTP effluent was found to be a reliable cooling water resource, it can provide the NPP with cooling water. It increases annually and the current effluent of 100 MCM/yr is expected to increase to more than 130 MCM/yr by 2030, a 30 MCM/yr excess from the current production (which meets NPP allocated cooling water amounts). However, reliability of AsSamra's effluent nine quality parameters (pH, TDS, SO_4^{2-}, PO_4^{3-}, NO_3^{-}, Cl^{-}, DO, total and carbonate hardness) indicated that some of these parameters (TDS, Cl, total and carbonate hardness) exceeded the Russian cooling water standards and a tertiary treatment is required.

A groundwater modeling was developed using three dimensional finite difference Processing MODFLOW code. When simulating two pumping scenarios of: 30 MCM/yr and 15 MCM/yr pumping rates, the estimated drawdowns were 319.2 m and 160 m, respectively. Which exceed the allowable limit of one tenth of the aquifer thickness (around 100 m). Finally when limiting the drawdown to 100 m (10% of aquifer thickness), a pumping rate of 9.4 MCM/yr was obtained and considered as the maximum allowable pumping rate. Thus, the allocated quantities will not be met.

A general lack of data on the deep aquifers imposed certain constrains on the calibration of the developed MODFLOW groundwater flow model; calibration was performed for steady state conditions for horizontal conductivity by trial and error, while calibration could not be done for transient state conditions because the aquifers have not been pumped yet and therefore no drawdown data is available.

In addition, testing the water quality from the only well (AZ1) penetrating the deep (Ram) aquifer indicated that the TDS is 1560 mg/L which far exceeds the allowable Russian standards (800 mg/L). Thus, treatment is needed before using this water to cool the reactor.

RECOMMENDATIONS

The above conclusions are based on the results of analysis using available data and should be interpreted as a first feasibility test and further studies are needed with emphasis on data measurement and monitoring programs as follows;

AsSamra effluent parameters must be tested (frequently) specifically for (chloride, total and carbonate hardness parameters) to have a better data set for these parameters and therefore to choose the appropriate treatment technology and design.

Ram aquifer productivity must be tested by drilling testing wells that could be converted to exploitation wells. The recommended area to drill new wells is about some kilometers to the north or east of AZ1 to reach Ram aquifer.

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